Adapting the SHEL model in investigating industrial maintenance

Abstract

Purpose – The purpose of this paper is to identify and categorize problems in knowledge management of industrial maintenance, and support successful maintenance through adapting the SHEL model. The SHEL model has been used widely in airplane accident investigations and in aviation maintenance, but not in industrial maintenance.

Design/methodology/approach – The data was collected by two separate surveys with open-ended questions from maintenance customers and service providers in Finland. The collected data was coded according to SHEL model -derived themes and analysed thematically with NVivo.

Findings – We found that the adapted SHELO model works well in the industrial maintenance context. The results show that the most important knowledge management problems in the area are caused by interactions between Liveware and Software (information unavailability), Liveware and Liveware (information sharing), Liveware and Organisation (communication), and Software and Software (information integrity).

Research limitations/implications – The data was collected only from Finnish companies and from the perspective of knowledge management. In practice there are also other kinds of issues in industrial maintenance. This can be a topic for future research.

Practical implications – The paper presents a new systematic method to analyse and sort knowledge management problems in industrial maintenance. Both maintenance service customers and suppliers can improve their maintenance processes by using the dimensions of the SHELO model.

Originality/value – The SHEL model has not been used in industrial maintenance before. In addition, the new SHELO model takes also interactions without direct human influence into account. Previous research has listed conditions for successful maintenance extensively, but this kind of prioritization tools are needed to support decision making in practice.

Keywords - Industrial maintenance, SHEL, SHELO, knowledge management, information management, qualitative data analysis

Paper type Research paper

1 Introduction

Complex organizational structures, a multitude of disciplines and several reporting levels are often identified as problems in the maintenance function (Swanson, 2003). Tendencies towards integrated product and service offerings increase such complexity further (Pawar et al., 2009). Within the maintenance function, personnel with different skill sets, such as electricians, mechanics and pipe installers need to work together, and the management has to take this into account (Organ et al., 1997). In addition to organisational and managerial complexities, maintenance faces complexity related to technical and human learning aspects (Shafiei-Monfared and Jenab, 2012). All these together make resource allocation and work scheduling in maintenance a difficult task. Accordingly, computer support has become indispensable for tasks such as stock control, management of personnel, task tracking, processing of historical data and document change control (Waeyenbergh and Pintelon, 2002). Therefore, more attention must be paid to information processes to support the ability to make decisions that are appropriate in the situation at hand and take into account longer-term consequences without neglecting the crucial role human knowledge plays in maintenance. Decreasing the complexity of organisational structures or maintenance tasks are strategies for reducing the requirements of information processes (Swanson, 2003; Shafiei-Monfared and Jenab, 2012). Other strategies aim at increasing the capacity of an organization's information processing capability either by investing into information systems or by streamlining the decision making processes (Swanson, 2003; Crespo Marquez and Gupta, 2006), and integrating the maintenance function with other activities performed in the company through advanced IT systems (Sherwin, 2000). However, it is recognised that to support effective decision-making, the better the understanding of a problem the more successful the proposed solution can be (Triantaphyllou et al., 1997). For the investigation of the challenges in industrial maintenance, methods are required that can capture the multitude of different influences on successful maintenance, such as humans, technical systems and organisational settings (Thenent et al., 2013). Metso (2013) has identified problems in information sharing as well as lack of information in industrial maintenance. However, without proposing guidance or good practises for how to overcome these challenges. Thenent et al. (2013), having investigated the conditions for successful maintenance, suggest that the SHEL model offers potential for improved understanding of maintenance practices and conditions for successful maintenance. By combining these two perspectives in this paper (see Figure 1), we shed light on the information management challenges that arise in industrial maintenance from the interactions between the different elements in this complex system.

The SHEL model is a framework that can be used to study the interactions between individuals, the systems in which they function, and the environment that influences the individuals' activities (Hawkins 1987). Edwards (1972) presented the initial SHEL model which comprises three elements that interact with humans (called Liveware): Software, Hardware and Environment. Hawkins (1993) added the person-to person relationship (Liveware – Liveware) and called the resulting model SHELL. Hawkins focused on relationships between Liveware and Software, Liveware and Hardware, Liveware and Environment, and Liveware and Liveware. The SHELL model does not cover the relationships between Hardware-Hardware, Hardware-Environment, and Software-Hardware. Chang and Wang (2010) added the organizational element to the model and called it SHELLO.

The SHEL model is used in aviation in accident investigation and in aviation maintenance (see for example Licu et al., 2007; Edwards, 1981; Lufthansa, 1999) Other applications of the SHEL model include maritime organisations (Chen et. al., 2013). This paper demonstrates an application of a modified SHEL model in industrial maintenance. In this paper industrial maintenance includes:

- planned maintenance actions;
- unplanned repairs;
- calibration and testing;
- definition, planning, management and improvement of maintenance actions;
- internal and external collaboration between organisational units involved in industrial maintenance activities.

Figure 1. Phases of adapting the SHEL model in industrial maintenance

A key problem for service providers of maintenance is managing the ever-increasing information flow and system complexity. There is an increasing amount of digital product information and other data provided together with hardware and software products from manufacturers, subsystem suppliers and other sources (Candell et al. 2009). Attempts to resolve the challenges related to information sharing and communication between different parties in industrial maintenance include the implementation of advanced software solutions, such as Product Lifecycle Management Systems (Lee et al., 2008) and e-maintenance (Candell et al., 2009). However, as recognised by O'Dell et al. (1998), while software helps in information collecting and sharing, it does not solve all problems. Brax and Jonsson (2009) observed that maintenance management software was not frequently used in the setting they investigated, and the maintenance management software did not support automated data processing tools. The companies also suffered from a lack of business intelligent tools. Furthermore, fragmented maintenance information caused problems such as shipping of incorrect spare parts. In addition, feedback from customers was not gathered, which gave the impression that the company lacked interest in its customer. Moreover, lack of trust between the provider and its clients prevented successful collaboration. Communication between the different parties is one part of maintenance management. The correct management of maintenance information helps to develop the planning and scheduling of maintenance. This information is collected from the maintenance process and other relevant information (Barberá et al., 2012).

Within condition-based maintenance, the condition of the technical system is monitored and combined with fault diagnosis to support decision making about the appropriate maintenance interventions. Since the amount of collected data can be huge, it needs to be converted into useful form (Campos, 2009). Remote diagnostics has been used to collect data from customers' products and plants. Typically, a customer has staff with limited knowledge, and thus outside service support is required (Lee 1998). Data about a machine and its working environment is needed at any time. This information can be shared with other users, service providers as well as other functions inside the company. More research is needed on how to manage the information and distributed decision making (Lee, 1998).

The literature reveals that challenges in industrial maintenance tend to be tackled mainly through the implementation of more sophisticated IT systems and an increase of available data. However, frequently overlooked are the interdependencies of different elements involving human, organisational and technical factors that create the conditions for maintenance to be successful. The diversity of these elements is best approached through a qualitative data analysis which enables the integration of traditionally non-commensurable observations. We propose the use of the SHEL model in identifying the challenges in information processing in industrial maintenance to support the information flow within the maintenance function and between maintenance and other functions.

The literature review on successful maintenance and problems in industrial maintenance showed that all SHEL elements play a role in them. The analysis of the collected data showed which elements and relationships of the SHELO model – which is the SHEL model adaption we propose - are relevant in industrial maintenance. The contribution of this paper is a novel application and an extension of the original SHEL framework, focusing on identifying the most problematic aspects of maintenance knowledge management.

The remainder of this paper is structured as follows:

- Section 2: A literature review on the conditions for successful maintenance and an introduction to the SHEL model and its application;
- Section 3: An outline of the research methodology, including a description of the methods for data collection and data analysis using a modified SHEL model that incorporates organisational factors. Hence, it is named SHELO;
- Section 4: Findings are presented that demonstrate that the elements captured by the SHELO model and their relationships are suitable for capturing challenges in industrial maintenance;
- Section 5: Conclusions that highlight the value of the SHELO model in understanding the challenges in industrial maintenance and outlines further work aiming at developing means of supporting decision-making based on the findings of the study.

2 Literature review

Maintenance can impact many aspects significant for business, for example equipment downtime, quality and productivity (Shyjith et al., 2008). Here we define that for maintenance to be successful, the targeted availability of a technical system must be achieved when required (Thenent et al., 2013). This is not a simple goal and requires a systemic approach, since many different elements are connected to each other with causal relations that affect the outcome. These elements include e.g. people, machines and equipment, computers, software, and the environmental context. The importance of the competence of the personnel and training for successful maintenance has been acknowledged by many scholars (e.g. Al-Najjar, 2007; Al-Najjar and Alsyouf, 2003; Goettsche, 2005; Simões et al., 2011).

The number of maintenance outsourcings has been increasing (Taracki et al., 2009; Xia et al., 2011) despite the difficulties involved in measuring and evaluating the viability of a strategic decision to outsource (Gómes et al., 2009). In addition to outside service providers, also the original equipment manufacturers are increasingly interested in taking their own share of the maintenance business and shifting from a product-oriented business strategy to a service-oriented one. According to Candell et al. (2009), a service-oriented strategy requires harmonization of the maintenance process. In general, the networking development introduces new challenges for communication and cooperation, even within the same organisation in making maintenance successful. For example, information exchange between technicians and equipment operators is of utmost importance in maintenance (Aubin, 2004; Kinnison, 2004; Leney and Macdonald, 2010; Reiman, 2010).

2.1 Conditions for successful maintenance

Maintenance management is facing fundamental changes with the emergence of the industrial internet (or internet of things) (see e.g. Wang et al., 2013). Such changes include an expected increase of information flow, which leads to the development of more complex and technologically advanced information systems. These challenges arising from these trends, combined with the networking trend and the overwhelming amount of data can lead to severe problems with fragmented data due to lack of communication between people, organizations and technological systems (e.g. Candell et al., 2009; Ranasinghe et al., 2011).

The challenges and requirements of successful maintenance can be studied on different levels, from operative maintenance of single assets to strategic management of maintenance in companies or company networks. To address this variety, Table 1 below shows two different perspectives on the required conditions for success in maintenance. The left column lists the major elements to be discussed in a single maintenance contract according to standard SFS-EN 13269 (2006), while the right column presents the requirements for designing, implementing and maintaining asset management systems as listed in standards ISO 55000 (2014) and ISO 55001 (2014).

Table 1. Conditions for successful maintenance from the perspective of single contracts and on the system level (ISO 55000, 2014; ISO 55001, 2014; SFS-EN 13269, 2006)

MAINTENANCE CONTRACT LEVEL REQUIREMENTS	ASSET MANAGEMENT SYSTEM LEVEL REQUIREMENTS
▪ Determining the parties and their intentions ▪ Defining the main technical, commercial and legal terms ▪ Recognising the scope of the maintenance, e.g.: - operation and maintenance location, - task content, - time schedule, - impediments and delays ▪ Agreeing on the technical arrangements, e.g.: - verification, - technical information of the equipment, - supply of spare parts, materials and consumables ▪ Settling the commercial arrangements, e.g.: - prices and terms of payment, - warranties and incentives, - penalties/liquidated damages, - insurances and financial guarantee ▪ Making the organisational arrangements, e.g.: - providing conditions for performance, - health and safety specifications, - environmental protection, - security specifications, - quality assurance, - supervision/management, - keeping records, documentation ▪ Agreeing on the legal arrangements, e.g.: - property rights and copyrights, - confidentiality, - force majeure, - liabilities, - settlement of disputes, - reasons and formalities for termination	▪ Defining the context of the organisation: - external and internal issues, - the needs and expectations of stakeholders, - interaction with other management systems, - the asset portfolio covered by the system, - asset management strategy ▪ Providing leadership: - leadership and commitment (e.g. integration to business, ensuring resource availability and communication), - asset management policies, - organisational roles, responsibilities and authorities ▪ Good planning: - actions to address risks and opportunities, - establishing asset management objectives and ways to achieve them ▪ Ensuring support: - required resources, competence and awareness on e.g. policies, performance and risks, - internal and external communication, - information requirements and documentation ▪ Operations management: - operational planning and control, - management of change, - management of potential outsourcing ▪ Organising performance evaluation: - monitoring, measurements, analyses and evaluations, - internal audits and top management reviews ▪ Striving for improvement: - corrective and preventive actions, - continual improvement

Based on Table 1, the requirements on the level of single maintenance contracts seem to be technical by nature, whereas on the strategic system level the focus is more on communication and management. Overall, it can be concluded that the complex, diversified characteristics of maintenance call for systemic methods both in research and in actual maintenance management. In addition, maintenance is highly dependent on the decisions and competence of the personnel (Simões et al, 2011). To study the relationship of these human factors and the maintenance environment we have adapted the SHEL model in analysing our data on maintenance knowledge management, as suggested by Thenent et al (2013).

2.2 The SHEL model

Developed by Edwards (1972), the SHEL model is named after the initial letters of its elements Software (S), Hardware (H), Environment (E) and Liveware (L). The three elements 'L', 'H' and 'S' interact with each other and all of them interact with 'E', the environment. The relations are according to Edwards (1972): L, L-S, L-H, and L-E. The difference between L and L-L is that L-L signifies human interactions while Hawkins (1987) describes the characteristics of the central L in the SHELL model in engineering terms as:

- Physical size and shape
- Fuel requirements (food, oxygen, water)
- Input characteristics (senses)
- Information processing
- Output characteristics
- Environmental tolerances

Also psychological aspects, such as biases, mental conditions etc., as well as education and training can be seen as L elements. The term "Software" (S) is used to describe the rules, regulations, orders, laws, and procedures that govern the execution of tasks. "Hardware" (H) stands for physical features such as tools, material, objects, and equipment. As such, the 'L-H' combination denotes interactions of humans with technical systems. The environmental context 'E' represents for example the temperature, weather and noise the human is exposed to. Finally, the humans involved in the tasks are represented by 'L' as Liveware.

Hawkins (1987) introduced an evolution to the original SHEL model with the addition of a second L to place a stronger focus on the human side. While the new model captures all relations exhibited by the SHEL model, an L-L interface was added to reflect the interactions between humans. This L-L relation can for example capture interpersonal dynamics of flight crew functions as a group, leadership, crew cooperation and team-work. This way the SHELL model can capture relations of humans with other humans as well as interactions with the environment, machines (Hardware) and procedures or documentation (Software).

SHELL-Team represents a further evolution in which collaboration and communication with participants from distant locations or co-operative working in common contexts have been added (ICAO, 1997). The SHELL-Team (or SHELL-T) is applied in aviation maintenance tasks and process planning. In the area of nuclear power generation, Kawano (1997) found that the SHEL model was suitable for the explanation of human factors, team work and organizational effects. However, management factors such as organization, administration, safety culture etc., were considered not to be captured appropriately by the SHEL model. Therefore, Kawano (1997) proposed the m-SHEL evolution, where 'm' describes management factors separately from the other elements.

A systematic process for the investigation of human factors in seafaring has been presented by the International Maritime Organization (IMO). This process uses the SHEL model as a framework in addition to the Accident Causation and generic error-modelling system GEMS and Taxonomy of Error (IMO, 1999). Chen et al. (2013) use the SHEL model to describe preconditions in the Human Factors Analysis and Classification System for Marine Accidents (HFACS-MA).

The International Civil Aviation Organization (ICAO) highlights the organizational issues of airline maintenance operations (ICAO, 1998). Also the International Air Transport Association (IATA, 2006) defines five categories in the accident classification system: human, technical, environmental, organizational, and insufficient data. Chang and Wang (2010) have presented a new human-organization component and added it to the SHELL model. Hence, the resulting SHELLO model incorporates a new interaction between the Aircraft Maintenance Technician (AMT) and the organisation, Liveware-Organisation (L-O). The interactions captured by the SHELLO model comprise: L, L-S, L-H, L-E, L-L and L-O (Chang and Wang, 2010).

Cacciabue et al. (2003) have developed a model and simulation of the task performance of an AMT which combines the existing SHELL and RMC/PIPE (the Reference model of Cognition / Perception, Interpretation, Planning and Execution) models. RCM describes the cognitive and behavioural performance of human beings interacting with machines, using the four cognitive functions specified by PIPE. The simulator can be used in the development of AMT training programs and for the creation of maintenance procedures. The different dimension captured in the outlined SHEL model variations are listed in Table 2.

Table 2. Comparison of SHEL, SHELL, m-SHEL, and SHELLO models

Edwards (1972) SHEL	**Hawkins (1987) SHELL**	**Kawano (1997) m-SHEL**	**Chang & Wang (2010) SHELLO**
L	L	L	L
L-S	L-S	L-S	L-S
L-H	L-H	L-H	L-H
L-E	L-E	L-E	L-E
	L-L	L-L	L-L
		m	
			L-O

In industrial maintenance, human factors and other aspects that are not included in the original SHEL model, such as the organisations involved play a role (Chang and Wang, 2010). Unlike all the evolutions of the SHEL model discussed above, as shown in Table 2, we propose a model that is not focused on the interactions between humans and the other elements, i.e. human factors only. Hence, our model, called SHELO, can capture dimensions linking all elements to each other, as shown in Figure 2. For example, maintenance can be outsourced to an external service provider, which is reflected in the O-O dimension. More specifically, different computerised maintenance management systems (CMMS) may be in place in different organisations, and such a situation can be categorised by the S-S element. Accessibility to IT systems would fall under L-H interaction, the computer being the H (Hardware) and the user the L (Liveware).

Figure 2. The SHELO model.

Table 3 shows further examples of relevant factors in industrial maintenance and how they are categorised in the SHELO model.

Table 3. The contents of elements in industrial maintenance

	Content in industrial maintenance
S Software	Maintenance procedures Installation instructions Plans and schedules (Automated) algorithms of condition monitoring Regulation (regarding e.g. pressure vessels, nuclear power plantsetc.) Warranty clauses
H Hardware	Tools Materials Objects Equipment Computers Buildings / Physical infrastructure
E Environment	Environmental context Temperature, Noise Economic environment
L Liveware	Humans (operators, maintenance technicians, managers, designers, etc.) People interaction (L-L) Personal attitude Skills and education Availability of personnel
O Organisation	Organisational structure

3 Methodology

The research methodology used in this paper comprises two surveys for data collection and qualitative means to analyse the survey data. The steps of conducting the research are depicted in Figure 3 and explained in more detail below.

Figure 3. The phases of the conducted research

The survey questions were originally designed around information management and the identification of information gaps in industrial maintenance. The data collected for the study included in total 82 responses to two separate surveys from maintenance customers and service providers. The first survey was sent to 16 Finnish maintenance professionals who participated in continuous professional education at Jyväskylä University of Applied Sciences. Completing the survey was required in order to pass one of the respondents' courses, so a response rate of 100% was achieved. The second survey was sent to 327 professionals from 241 member companies of the Finnish Maintenance Society, Promaint. In the second survey a response rate of 20% was achieved, resulting in 66 complete responses. While the two surveys were separate, the questionnaires were similar for all participants. The answers to the open-ended questions were coded and thematically analysed with NVivo version 10 software.

4 Findings – the SHELO model in industrial maintenance

Applying the SHELO model to the survey data showed that the L-S, L-L, L-O and S-S themes presented in Table 4 comprised the highest number of coded text passages. There were no codes in the elements S-E, H-E, H-O, E-E, H and E. One explanation for this is that the survey questions did not explicitly touch on aspects such as the environment, organisations or hardware-related concepts, such as tools and materials.

Table 4. The SHELO dimensions and number of codes for each category

		S		H		E		L		O	
S	34	S-S	0								
H	1	S-H	2	H-H	6						
E	0	S-E	0	E-H	0	E-E	0				
L	4	L-S	31	L-H	7	L-E	2	L-L	31		
O	2	S-O	6	O-H	0	E-O	1	L-O	23	O-O	7

Tables 5 to 9 (and in appendix A) show results that emerged when coding the survey answers employing the SHELO model-derived concepts. Since the survey contained open-ended questions, some answers were quite long and Tables 5 to 9 exhibit what we consider the most insightful results. The codes in dimension L, Liveware, mainly referred to personal attitude. More details about the results of this element can be seen in Table 5 below.

Table 5. Liveware (L) findings

L (Liveware)
Misunderstandings cause information breakdowns because the other parties do not understand the criticality of the situation. Another issue is misunderstandings about the schedules and the scope of the service.
The priorities of the maintenance tasks are inadequate. Each group considers only their own point of view to the maintenance, and no one wants to take overall responsibility or provide it to others.
Due to the hectic pace, things stay untreated.
When the workload increases, the information exchange is not done properly.

The total number of codes in the L-S element was 33. Table 6 shows a selection of six replies that were considered representative for the codes in this element. The L-S codes typically highlight a lack of information, information that was not updated, or information that was available but could not be found when needed. Other aspects concern instructions that were not updated or improper documentation. Ideas for improvements comprised meetings, closer co-operation and linking the IT networks between the organisations/individuals involved.

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Table 6. Liveware-Software (L-S) findings

L-S (Liveware – Software)
It is difficult to find information about equipment, such as dimensions, design of past projects.
Maintenance Instructions were not up-to-date.
Customers could not provide the error messages of the production machines because information was not available.
The recorded information such as fault information is inadequate or unreliable.
The downtime work is not scheduled or the schedules do not include all tasks required.
Maintenance procedures are not documented precisely.
Required information such as plans and schedules are not easily available or the information is unreliable. Schedules are not known early enough.
Required production information is not recorded in the CMMS system.
To acquire the information required to solve a problem, additional communication or interviews with service providers are needed.
The maintenance tasks are not described as processes, or instructions are not followed. Work is done the way it has always been done. This could be prevented by acting according to agreed uniform processes.
Information is usually available in some place, but not found.
Equipment registers do not pointi to the right serial number of the equipment.
The information sharing process is not documented.
***Several times:* Maintenance tasks are carried out according to the information available and may require reworking when more information becomes available.**
Respondents' suggestions for improvements
Co-operation with other maintenance partners should be improved to avoid information gaps.
Work planning is in an essential role in collecting information. The anticipation (of what) and preparation well in advance eliminates the problems of access to information.
Information can be found by networking with all maintenance partners.
Equipment registers should be exact and contain sufficient information.

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The most prominent challenge identified in the L-L (Liveware – Liveware) element was related to individual's attitudes. Furthermore, communication problems were described, including a lack of information sharing between individuals. More details are shown in Table 7.

Table 7. Liveware-Liveware (L-L) findings

L-L (Liveware – Liveware)
Communication between the customer and the supplier is important. Too distant attitude towards each other breaks the information flow.
The customer is unwilling to provide the information required.
Functional and compact meeting practice reduces information gaps. Emails and the use of production logs as an information channel reduces the impact of data outage.
***Several times:* Lack of communication and instructions: − Something must be done without sufficient information − When information is available, changes to the maintenance done are required to complete the task.**
The needed information is kept by a single person.

As depicted in Table 8, the L-O element revealed problems in communication between people from different organisations or departments, as well as areas of unclear responsibility. Ideas for improving communication included greater flexibility between departments and autonomy to identify and implement solutions that support information sharing.

Table 8. Liveware – Organisation (L-O) findings.

L-O (Liveware – Organisation)
Unclear responsibilities for example about spare parts, modifications and how systems are maintained.
Communication problems when information is passed through too many levels in the organisation.
Maintenance support is not reachable.
Rush and lack of resources can cause a situation in which it is assumed that everybody involved knows everything that is required.
Customers do not know the reasons for equipment malfunction.
***Several times:* Changes in personnel e.g. the contact person, cause a lack of information as well as faceless trading.**
Respondents' suggestions for improvements
Add flexibility between departments to improve communication.
Encourage personnel to identify and take advantage of new solutions.
Problems could be easily reduced by improving communication with the maintenance service providers.
The maintenance service provider has to be selected carefully by the customer. In addition, the work should be defined precisely.
Problems in information sharing can be avoided by organising information sharing and the use of CMMS systems.

The S element concerns concepts related to procedures and information processing through computer systems. A typical problematic situation in the S element was wrong or incomplete information. The most important improving idea was to verify data when entering it into a CMMS system. Further findings are presented in Table 9.

Table 9. Software (S) findings

S (Software)
The importance of smooth routine maintenance to avoid the workload of maintenance designers.
Lack of spare parts due to a missing purchase order.
Maintenance software systems are often bought with an ERP system and do not fulfil the needs of the maintenance personnel.
Not enough history data available on the maintenance system
The statistics of defect data is unreliable.
IT interface challenges, for example connecting to the maintenance target with CMMS when wireless data transmission is forbidden for safety reason, and no other IT connection is available.
Documentation is not updated, for example a spare part list of a new machine was not updated and only the older machine version's spare part list was available.
Difficulty in ordering spare parts because the equipment has many different spare part catalogues and manuals.
Difficulty to provide comprehensive and precise information in the reporting system.
Maintenance costs contain also other than maintenance work.
Required production information is not recorded in the CMMS system.
***Several Times:* Needed data is not available in the maintenance system**
Respondents' suggestions for improvements
A mobile maintenance software system would help prevent lack of information. The system could be easily implemented with customers.

In the maintenance software system it is essential to enter the data into the system, *verify* the data, take advantage of the data and *deliver the data to everybody*.
Setting clear priorities and focusing on important maintenance tasks accompanied by good instructions will raise the quality of maintenance work.

The results of the elements L-H, L-E, S-H, S-O, H-H, H, E-O, O-O and O are presented in appendix A due to the small number of codes in each of them. Element L-H with 8 codes received the highest number of codes for the elements presented in appendix A. Even though there were important aspects, such as communication and insufficient information, we focused the representation of results on the elements with a higher number of codes.

Using the SHELO model as a basis for coding was shown to provide useful insights into the challenges in industrial maintenance. While previous research using the same data (Metso 2013) highlighted challenges in communication and information sharing, application of the SHELO model provided insights into how other influencing factors such as organisations and individuals relate to each other. In addition, the SHELO model was able to incorporate such findings as the challenges related to procedures and IT systems (S-S) that would have remained hidden in the original SHEL model due to the lack of direct human (L) interaction. This way the SHELO model can provide a novel perspective on industrial maintenance to account better for the diversity of influencing factors when making decisions on maintenance practices.

5 Conclusions

This paper demonstrates the application of a modified SHEL model to analyse survey data about information and knowledge management in industrial maintenance. To the best of the authors' knowledge this is the first application of the SHEL model in such a context. While the original SHEL model was created to investigate human factors in accidents, we adapted the model to capture organisational factors as well, and that is why our model is called SHELO. The SHELO model, unlike the other variations of the SHEL model, takes interactions without direct human influence into account. Such variation is useful in modern maintenance management and the related research, because more and more information is transferred and processed without direct human interaction. Our analyses show that the most relevant knowledge management problems in industrial maintenance are in the following areas:

- Interactions between humans and procedures and IT systems, categorised as Liveware-Software within the SHELO model, with emphasis on the unavailability of information;
- Interactions between humans, Liveware-Liveware, where the emphasis is on communication and attitudes towards information sharing;
- Humans as Liveware and Organisation, which comprises communication between organisations and departments and their respective responsibilities;
- Software, including procedures and IT systems that provide incomplete or flawed information.

The SHELO model proved to be a useful framework for analysing industrial maintenance systematically. It allows categorising identified problems to conduct further analyses on specific problem areas and to identify appropriate solutions. Our study demonstrates shows that problems of knowledge management in industrial maintenance can be identified by analysing survey data with categories contained in the SHELO model. In addition to problems, we identified propositions for improving maintenance activities and knowledge management in industrial maintenance. Problems in information sharing can be reduced by improving communication with service providers and using CMMS systems. While the existing literature and standards list an extensive number of conditions for successful maintenance, in practice prioritisation tools are needed to support the decision making. Applying the SHELO model can assist maintenance service customers, suppliers and designers in improving maintenance processes and planning.

The research was limited to the identification of information gaps and information sharing problems, as this was what the surveys were originally designed for. For example, environmental and organisational issues were not explicitly raised in the survey questionnaire. In future research, a case study could be executed, capturing an industrial maintenance provider and a customer in the same project to identify whether problems and suggestions for improvement differ between the organisations involved. Furthermore, a new survey specifically designed around the SHELO elements can be employed to gain a broader understanding of the current challenges in industrial maintenance, comparing different companies in Europe or internationally, in a specific sector or across sectors.

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7 Appendix A

L-H (Liveware – Hardware)
Needed information should be recorded centralised to software which everybody who needs information can have access to, and also the search function is user-friendly.
CMMS system is available but not properly used.
Spare part availability information should be in a system with easy access.
Customers do not know how to use the ERP systems' maintenance parts effectively.
CMMS system's effective use.
Taking part in equipment replacement projects would be beneficial for maintenance workers to learn about the specific equipment maintenance.
Poor usability of CMMS, which means the relevant data cannot be entered by the maintenance personnel.
L- E (Liveware – Environment)
Focus on finding out causes, not finding out who is guilty.
Machines were in motion and the quality was just tolerable. The daily work was only fixes and controls.
S- H (Software – Hardware)
Spare part lists were not available
Needed information must be searched from files, documents, archives, supplier, designers, etc.
S- O (Software – Organisation)
The customer and maintenance service provider do no enter data to the CMMS systems properly.
A wide own organisation helps to find needed information from own data sources.
The customer and service provider must have data exchange instructions.
Customers cannot find the right information because it is not available.
Information is usually provided by our own company or by the equipment supplier. Sometimes maintenance work is carried out according best information available, requiring subsequent modifications frequently.
When the maintenance service is organised by several maintenance suppliers, lack of information is common. For example, the customer might change the schedule or the content of maintenance without informing the other parties.
H – H (Hardware – Hardware)
Reports from the supplier are not transferred to the CMMS.
The customer and supplier have different CMMS systems.
Instructions are located in different software systems.
***Several times:* Problems with software systems.**
H (Hardware)
During the maintenance work a design error was found.
E - O (Environment – Organisation)
More attention should be paid to preventive maintenance.
O - O (Organisation – Organisation)
Responsibility between the organisations is not clear.
There are many parties involved in maintenance projects. They do different software systems and too many people take part in maintenance. Also financing can be from a different organisation.
Many organisations have different kinds of information in maintenance.
A long approvals chain
Fragmentation in organisations and rapid changes.
The customer's maintenance does not support multi-vendor networks.

The customer has not been aware of the scheduling of production line maintenance.

O (Organisation)
The supplier's spare part services are available only during office hours, so it can take some time to get help.
The operational models are not designed for a multi-vendor environment.